NSWCCD-61-TR–2004/16 The Influence of Processing on the Microstructure and Properties of the Titanium Alloy Ti-5111

Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2004/16 **September 2004**

Survivability, Structures, and Materials Department
Technical Report

The Influence of Processing on the Microstructure and Properties of the Titanium Alloy Ti-5111

by
Amy C. Stauffer, Ernest J. Czyryca
and
Donald A. Koss
The Pennsylvania State University

Approved for public release; distribution is unlimited.

Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR–2004/16 September 2004

Survivability, Structures, and Materials Department

Technical Report

The Influence of Processing on the Microstructure and Properties of the Titanium Alloy Ti-5111

by

Amy C. Stauffer, Ernest J. Czyryca

and

Donald A. Koss

The Pennsylvania State University

University Park PA 16802

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

REPORT DATE (DD-MM-YYYY)
09 2004

2. REPORT TYPE
FINAL

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
The Influence of Processing on the Microstructure and Properties of the Titanium Alloy Ti-5111

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Amy C. Stauffer, Ernest J. Czyryca (NSWCCD) and
Donald A. Koss, The Pennsylvania State University

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
NAVAL SURFACE WARFARE CENTER
CARDEROCK DIVISION (CODE 614)
9500 MACARTHUR BLVD
WEST BETHESDA MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-61-TR–2004/16

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
CHIEF OF NAVA RESEARCH
ATTN ONR-332
BALLSTON CENTRE TOWER ONE
800 N QUINCY STREET
ARLINGTON VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The physical, mechanical, and corrosion properties of titanium and its alloys are attractive for applications in the U.S. Navy in view of design requirements for increased reliability with reduced maintenance and weight. The Naval Surface Warfare Center, in cooperation with Titanium Metals Corporation, developed the Ti-5Al-1Sn-1Zr-1V-0.8Mo (Ti-5111) alloy as a lower cost alternative to previous high-strength titanium alloys exclusive to Navy applications. The influence of heat treatment on the microstructure and mechanical properties was examined in the Ti-5111 alloy in both wrought and cast products. The effects of time and temperature on the microstructural evolution in this near-alpha alloy are assessed, and the relationships between microstructure and the corresponding tensile properties as well as impact and fracture toughness behavior are examined.

15. SUBJECT TERMS
Microstructure
Properties
Titanium Alloy Ti-5111
microstructural evolution
near-alpha alloy

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	24	AMY C STAUFFER
					19b. TELEPHONE NUMBER *(include area code)* 301.227.5008

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Contents

Figures

Tables

Administrative Information

The work described in this report was performed by the Metals Division (Code 614) of the Survivability, Structures and Materials Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD), West Bethesda, MD. The Office of Naval Research (ONR), Arlington, VA. funded the work through the Seaborne Materials Technology Program. The Naval Sea Systems Command (NAVSEA Code SEA 05M2) Washington, D.C. is the Technical Authority for this work.

Acknowledgements

The work discussed in this paper was conducted in support of a Naval Undersea Systems Center (NUWC – Newport RI) project under Mr. Noah Forden of the Newport Division. The hot rolled and annealed plate was provided by TIMET. The cast plates were provided by PCC, Inc. The metallurgical study was sponsored by ONR through the Seaborne Materials Technology Program under Dr. Julie Christodoulou. The assistance of all of these partners is gratefully acknowledged.

This page intentionally left blank

Executive Summary

The physical, mechanical, and corrosion properties of titanium and its alloys are attractive for applications in the U.S. Navy in view of design requirements for increased reliability with reduced maintenance and weight. The Naval Surface Warfare Center, in cooperation with Titanium Metals Corporation, developed the Ti-5Al-1Sn-1Zr-1V-0.8Mo (Ti-5111) alloy as a lower cost alternative to previous high-strength titanium alloys exclusive to Navy applications. The influence of heat treatment on the microstructure and mechanical properties was examined in the Ti-5111 alloy in both wrought and cast products. The effects of time and temperature on the microstructural evolution in this near-alpha alloy are assessed, and the relationships between microstructure and the corresponding tensile properties as well as impact and fracture toughness behavior are examined.

Introduction

Titanium alloys provide an excellent combination of mechanical and physical properties for marine applications. Their high specific strength, good fracture toughness, excellent marine corrosion and erosion resistance, and acceptable weldability makes them desirable candidates for weight-critical structural and machinery applications in shipbuilding.[1,2] Thus, titanium and titanium alloys are used in increasing applications for U.S. Navy ships. Commercially Pure (CP) titanium grades, such as Ti-3Al-2.5V alloy, and the widely-used alpha-beta Ti-6Al-4V ELI grade alloy are currently in use.[3] Ti-6Al-4V ELI grade is considered the high-strength option for marine applications. However, fracture toughness and stress corrosion cracking resistance of Ti-6Al-4V ELI and welds are insufficient for critical applications, particularly under shock conditions.[1]

The Ti-5Al-1Sn-1V-1Zr-0.8Mo (Ti-5111) alloy was developed as a lower cost, more producible Ti-base alloy with properties similar to the Ti-100 alloy (Ti-6211, Ti-6Al-2V-1Nb-1Ta)[4] which was developed to meet a Navy 100 ksi (690 MPa) minimum yield strength requirement while maintaining toughness and weldability for deep submergence vehicles.[5] The Ti-5111 alloy is a near-alpha alloy with maximum oxygen content of 0.11 weight %. Alpha-soluble alloy elements of aluminum (Al), tin (Sn), and zirconium (Zr) were added for increased strength while silicon (Si) is present to enhance creep resistance, strength, and toughness. The presence of Zr promotes a uniform silicide distribution in the matrix material. The β-stabilizers, vanadium (V) and molybdenum (Mo), have a small beneficial effect on strength; however, Mo has a strong effect in improving toughness.[6,7]

Although the Ti-5111 alloy was initially developed in the late 1980s, studies to enhance properties by heat treatment and microstructure control were limited. For this study, Ti-5111 plate from production ingots and investment cast Ti-5111 in plate form were used. The purpose of this study was to examine the influence of heat treatment on the microstructure and selected mechanical properties of Ti-5111 in both wrought and cast plates.

Experimental Procedure

Materials

Titanium Metals Corporation (TIMET) produced a 4500-kg ingot of Ti-5111 that was converted to 25- and 50-mm thick plates. Previous studies indicated that the optimum properties of Ti-5111 wrought products were achieved by hot rolling above the β-transus temperature of 980 °C (1795 °F).[7, 8] For this study, hot rolling in the β-phase field was followed by annealing in the α/β field at 955 °C (1750 °F) for one hour per 25 mm of section thickness and air cooling. Both the hot-rolled and annealed and the cast Ti-5111 plates were 25-mm thick. The chemistry of the hot rolled and cast plates and the ASTM B 265 Grade 2 specifications are provided in Table 1.

Table 1: Chemistries for Ti-5111 Wrought and Cast Plates

Element	ASTM B 265 Grade 32	Hot-rolled Plate (wt%)	Cast Plates (wt%)
Al	4.5-5.5	5.01	5.09
V	0.6-1.4	1.03	1.01
Zr	0.6-1.4	1.06	1.00
Sn	0.6-1.4	1.02	0.97
Mo	0.6-1.2	0.76	0.82
Si	0.06-0.14	0.091	0.09
Fe	0.25 max	0.096	0.03
Cu	0.1 max	-	0.03
Mn	0.1 max	-	0.01
O	0.11 max	0.089	0.10
N	0.03 max	0.003	0.016
H	0.015 max	-	0.001
C	0.08 max	0.009	< 0.01

Two plates, 30.5 cm x 30.5 cm x 2.54-cm thick, were investment cast by PCC-Structurals, Inc. and subsequently hot isostatically pressed at 900 °C (1650 °F) and 103 MPa for two hours. The plates, designated Casting A and Casting B, were given different heat treatments. Casting A was vacuum annealed at 843 °C (1550 °F) for two hours and subsequently "slow-cooled" about 32 °C/hour (90 °F/hour) to 538 °C (1000 °F). The plate was then transferred to an interlock chamber for an argon gas cool to room temperature. Casting B was annealed above the β transus at 1010 °C (1850 °F) for one hour and then "rapidly cooled" at a rate of approximately 38 °C/minute (100 °F/minute) in recirculated argon.

Specimens were prepared for metallographic examination by using polishing media consisting of 6 μm diamond solution followed by 0.05 colloidal silica with 30% H_2O_2 and subsequently etched with Kroll's reagent.

Mechanical Testing

Both the wrought and cast Ti-5111 plates were subject to tensile, Charpy V-notch (CVN) impact toughness, and 5/8″ dynamic tear testing (DT). Fracture toughness testing using compact tension, type 1TC(T), specimens was also conducted. Tensile testing consisted of standard, round 12.8-mm diameter specimens tested in accordance with ASTM E 8 at a strain rate of 10^{-3}/s and ambient temperatures. Charpy impact testing was conducted according to ASTM E 32, dynamic tear tests to ASTM E 604, and fracture toughness tests to ASTM E 1820 with 25-mm thick compact specimens. Scanning electron microscopy (SEM) was used to analyze the fracture surfaces on the failed specimens.

Results and Discussion

Ti-5111 Hot-rolled & Annealed Plate

Metallographic examination of the hot-rolled plate showed a Widmanstatten microstructure consisting of coarse, basketweave alpha phase in a matrix of transformed beta, as shown in Figure 1. The microstructure is typical for hot-rolled plate in the beta phase field followed by an α/β anneal just below the beta transus. The post-processing anneal coarsens the lath structure of the alpha phase producing the somewhat blocky alpha phase shown in Figure 1.

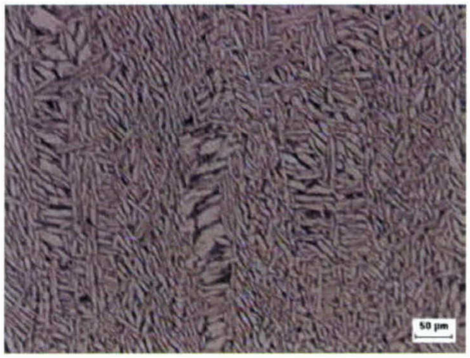


Figure 1: Optical micrograph of hot-rolled Ti-5111 plate showing coarse Widmanstatten alpha in a matrix of transformed beta.
(micrograph taken from long transverse surface of plate)

Table 2 shows the tensile properties of the hot-rolled Ti-5111 plate exceed the minimum strength and ductility requirements set by ASTM B265 for Grade 32 for the alloy. Both the ultimate tensile strength (UTS) and the yield strength (YS) were above the minimum specified values. The material exhibited a slight anisotropy with higher strengths being observed when the tensile axis was in the T-L orientation (transverse to the rolling direction). As shown in Table 3, the Charpy V-notch impact energy (particularly at higher temperatures) was also greatest when the test specimen was oriented in the transverse (T-L) direction with respect to the plate rolling direction. Comparison of the dynamic tear results to the target values indicates good toughness in the material at all temperatures tested. ASTM B265 does not specify impact or fracture toughness requirements; therefore, the target values listed in Table 3 are based on Navy requirements for Ti-100.

Table 2: Tensile Test Properties of Ti-5111 Wrought Plate

Test Direction	UTS (MPa)	YS (MPa)	EL (%)	RA (%)
L-T	835	728	12.5	24.4
T-L	855	753	12.0	24.8
ASTM B265 Grade 32	690 min	590 min	10.0 min	25.0 min

Table 3: Impact Toughness Properties of Ti-5111 Wrought Plate

Test Direction	Test Temperature (°C)	CVN Impact Energy Absorbed (J)	5/8" DT Energy Absorbed (J)
L-T T-L	22 22	41,42,42 57,54,56	624,587 X
L-T T-L	-2 -2	42,43,43 54,52,52	X X
L-T T-L	-40 -40	38,40,41 42,41,43	431,458 X
L-T T-L	-62 -62	35,36,36 38,37,38	373,407 X
Target Values	@ -2	37	270

Fractography of the tensile specimens indicated ductile fracture process with microvoid dimples and tear ridges in the more ductile β phase as shown in Figure 2. In contrast, the cleavage-like fracture surface of the hexagonal α phase (within the equiaxed α colony in the center of Figure 2) suggests fracture at a small strain, much less than the more ductile body center cubic β phase interspersed within and surrounding the colony.

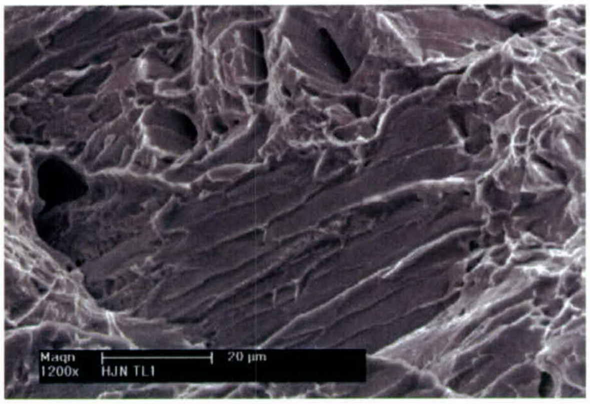


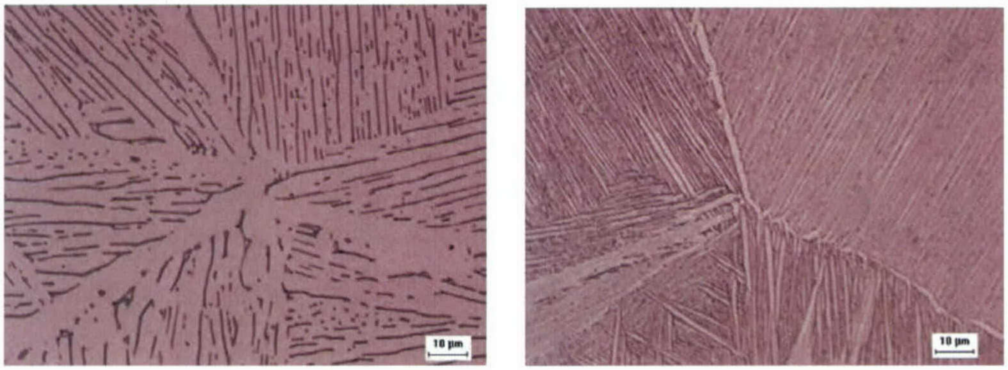
Figure 2: Fractograph of failed tensile specimen showing tear ridges within the ductile beta phase

Ti-5111 Cast Plates

The influence of heat treatment on the microstructure and selected mechanical properties of cast Ti-5111 was also examined. Casting A was given an α/β anneal heat treatment at 843 °C, followed by slow cooling, such as is common for near-alpha cast titanium alloys.[7] This annealing scheme caused the material to develop a coarse transformed beta microstructure, Figure 3(a), that consists of predominantly plate-like, aligned alpha phase with small amounts of retained transformed beta phase.

Casting B, which underwent a β-anneal at 1010 °C for 1 hour and was subsequently rapid-cooled, produced a fine-scale transformed beta structure. Casting B, shown in Figure 3(b), shows the triple point of three grains and an acicular alpha phase that is much finer than in Casting A. Some regions of Casting B showed a well-developed basket-weave alpha in a matrix of transformed beta, as is suggested in the lower region of Figure 3b. Due to the increased cooling rate for Casting B, the microstructure from Casting B is much finer than that in Casting A, and more beta phase is retained after the β-anneal. Both Castings A and B had similar prior beta grain sizes of ~1.5 mm.

The tensile properties for both castings, shown in Table 4, also exceeded the target minimum values for strength and showed even higher yield strengths than the typical values for the Ti-5111 rolled plate. However, the tensile ductility of the castings was generally below targeted values which is likely due to the large grain size of the castings. The β-annealed and rapidly cooled Casting B showed greater elongation than the α/β-annealed and slow-cooled Casting A.



(a) Casting A **(b) Casting B**

Figure 3: Optical micrographs showing transformed beta microstructures in Ti-5111 in Casting A and Casting B

Table 4: Tensile Properties for Cast Ti-5111

Material	UTS (Mpa)	YS (Mpa)	EL (%)	RA (%)
Casting A 843 °C vacuum anneal	783	751	8.6	15.3
Casting B 1010 °C β-anneal	820	756	10.2	15.8
***Target*:** ASTM B 265, Grade 32	690 min	590 min	10.0 min	25.0 min

The results from the CVN and DT tests are shown in Table 5. Both castings performed well above the minimum accepted values required for Ti-5111 weld metal. The two specimens from Casting B had slightly higher dynamic tear values than Casting A which may be due to the increased β-phase retained during rapid cooling from the β-anneal.

Table 5: Impact Toughness Properties for Cast Ti-5111

Material	**CVN Impact Energy Absorbed @ -2 °C (J)**	**DT Energy Absorbed @ -2 °C (J)**
Casting A: 843 °C vacuum anneal	60,61,57	407,353
Casting B: 1010 °C β-anneal	60,58,52,57,58	420,502
Target: NAVSEA requirements for Ti-5111 Weld Metal	37 minimum	271 minimum

Fracture toughness test results for both hot rolled and annealed and cast Ti-5111 plates are provided in Table 6. The specimens were tested to determine the plane-strain ductile fracture initiation toughness (J_{IC}). The J_{IC} data can be converted to the fracture toughness of a material (K_{MAT}) by the following equation:

$$K_{MAT} = J_{IC} * [E/(1-\upsilon^2)]$$

where E is the elastic modulus and υ is Poisson's ratio. The ratio, K_{MAT} / YS, provides an indication of the structural integrity and flaw tolerance of a material under shock load. The material is considered to have good potential structural integrity and flaw tolerance as this ratio approaches 1.0.

Table 6 shows the fracture toughness for the 'hot-rolled and annealed' plate is significantly higher than for the cast plates with the K_{MAT} / YS ratio of the hot rolled and annealed plate approaching 1.0. These preliminary data also suggest that Casting A has a higher toughness than Casting B although the CVN results in Table 5 suggested little difference between these two heat conditions and the DT results indicate the β-anneal and quench improve toughness. A more extensive investigation of the fracture toughness of these castings is in progress.

Table 6: Fracture Toughness Test Results for Cast Ti-5111

Material		J_Q (kPa-m)	K_{MAT} (MPa $^{1/2}$)	YS (MPa)	K_{MAT} / YS
Casting A: 843 °C vacuum anneal		**X**[a] 77	**X**[a] 99	**X**[a] 751	**X**[a] 0.81
Casting B: 1010 °C β-anneal		45 54	77 77	 756	0.62 0.67
Hot rolled & Annealed Plate	T-L	110	123	753	0.93
	L-T	96	113	728	0.85

Note:
[a] X = no data due to corrupted digital data file

An examination of the fracture surfaces of both castings indicate that, while the surfaces have similar appearances, there are significant differences between the fracture surfaces of Casting A and Casting B. Representative fracture surfaces from dynamic tear specimens for each casting condition are shown in Figure 4. For the case of Casting A, Figure 4(a), the fracture surface consists of large facets extending across alpha colonies, indicated by the arrows. At higher magnifications, Figure 4(b), low-energy fracture within the α-platelets is visible, as is the higher-energy, more-ductile fracture within the lighter, β-phase regions.

The fracture surface of Casting B suggests a higher energy fracture process consistent with the tear results in Table 6. Extensive regions exhibit ductile microvoid fracture with small microvoids forming in the retained (transformed) β phase as shown in Figures 4(c) and 4(d).

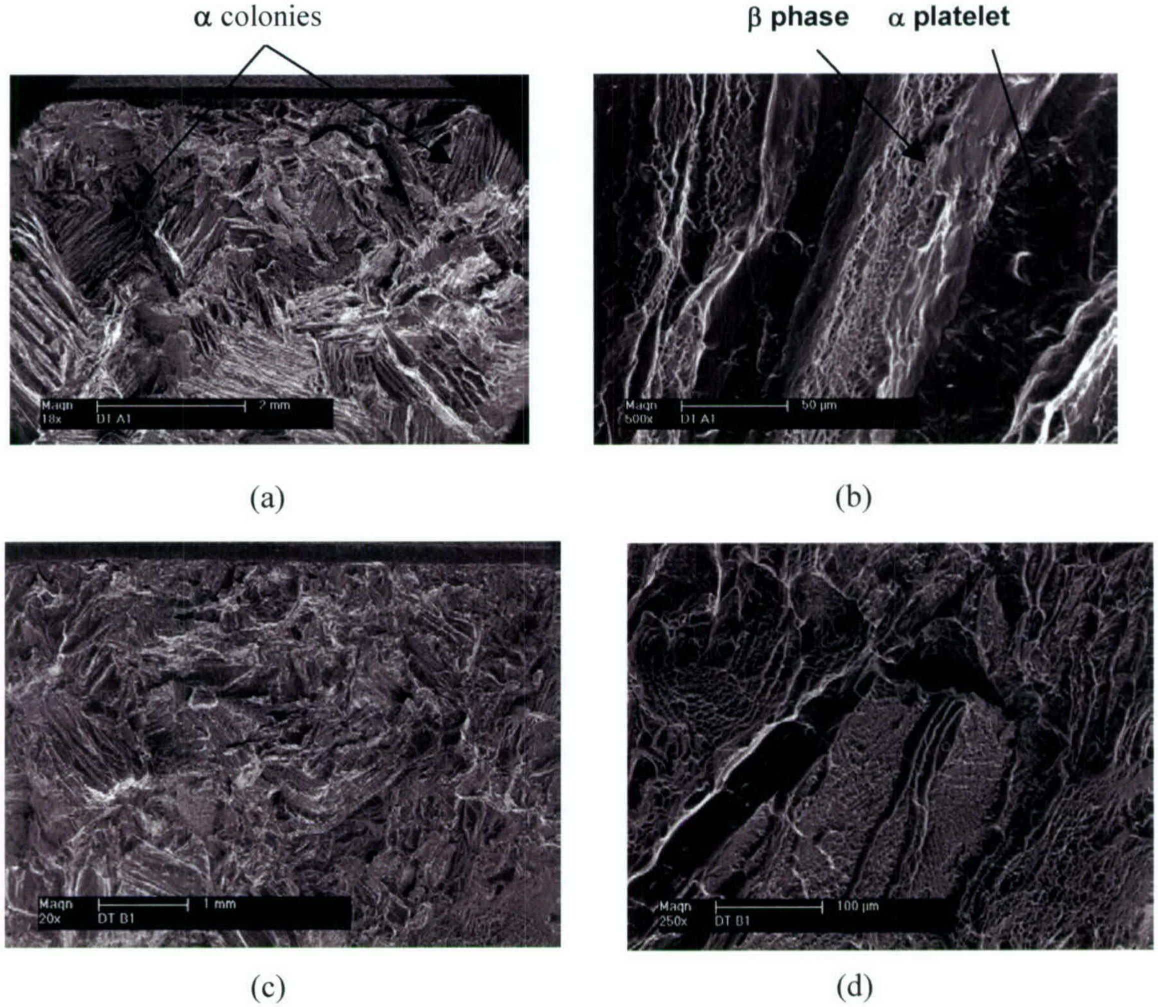


Figure 4: SEM micrographs for dynamic tear specimens for Casting A (a,b) and Casting B (c,d)

Conclusions

The influence of heat treatment on the microstructure and selected mechanical properties of Ti-5111 have been examined for plates produced by either hot rolling above the beta transus temperature or investment casting. Following an α/β anneal, the hot-rolled Ti-5111 plate was characterized by coarse Widmanstatten alpha in a transformed beta matrix and tensile properties that exceeded the properties specified in ASTM B265, Grade 32 for Ti-5111. Impact toughness results show a small sensitivity to temperature such that good impact and dynamic tear toughness is retained at –62 °C.

The cast Ti-5111 was examined in two heat-treated conditions: (a) α/β anneal at 843 °C and slow-cooled and (b) β anneal at 1010 °C and rapidly cooled. Preliminary results showed the cast material displayed a sensitivity to heat treatment in that a β anneal and rapid cooling condition exhibit a fine-scale, acicular, alpha microstructure resulting in improved impact toughness and tear ductility. While the strength, Charpy impact, and dynamic tear properties of the castings exceeded the target values, the fracture toughness for both castings, as well as tensile elongation for Casting A, are currently below the target. Comparison of the toughness results for Casting A and Casting B yielded mixed results; thus, further investigations are required to relate microstructure, heat treatment, and toughness.

References

[1] Czyryca, E. J., M. E. Wells, and K. Tran, "Advanced Marine Materials: Technology & Applications," *Proceedings, The Royal Institution of Naval Architects*, London, UK (2003) pp. 41-49.

[2] Been, J., K. Faller, *JOM*, June 1999, pp. 21-24.

[3] Tregoning, R. L., D. M. Aylor, and I.L. Caplan, *Titanium '95: Science and Technology* (London: IOM, 1996), pp. 1726-1733.

[4] Been, J., Paper No. 00641, CORROSION 2000, *NACE International*, Houston TX (2000).

[5] Bania, P. J., P. G. Allen, and W. M. Parris, *Titanium '95: Science and Technology* (London: IOM, 1996), pp. 1726-1733.

[6] Collings, E. W., "The Physical Metallurgy of Titanium Alloys," *American Society for Metals*, Ohio, 1984, pp. 39-72.

[7] Donachie, M. J., Jr. "Titanium: A Technical Guide," 2nd Ed., *ASM International*, Ohio, 2000, pp. 13-64.

[8] Burger J. A., and D. K. Hanink, *Met. Prog.* Vol 91, Jun 1967, pp. 70-75.

Distribution

	Copies
DOD – CONUS	
CHIEF OF NAVAL RESEARCH ATTN ONR 332 (J CHRISTODOULOU) BALLSTON CENTRE TOWER ONE 800 NORTH QUINCY ST ARLINGTON VA 22217-5660	1
COMMANDER ATTN SEA 05M NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5130 WASHINGTON NAVY YARD DC 20376-5130	1
COMMANDER ATTN SEA 05M1 (D THOMAS) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5131 WASHINGTON NAVY YARD DC 20376-5131	1
COMMANDER ATTN SEA 05M2 (G MITCHELL) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5132 WASHINGTON NAVY YARD DC 20376-5132	1
COMMANDER ATTN SEA 05P1 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5141 WASHINGTON NAVY YARD DC 20376-5141	1
COMMANDER ATTN SEA 05P2 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5142 WASHINGTON NAVY YARD DC 20376-5142	1
COMMANDER ATTN SEA 05P2 (J A MANUEL) NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5142 WASHINGTON NAVY YARD DC 20376-5142	1
COMMANDER ATTN SEA 05P3 NAVAL SEA SYSTEMS COMMAND 1333 ISAAC HULL AVE SE STOP 5143 WASHINGTON NAVY YARD DC 20376-5143	1
COMMANDER ATTN SEA PMS 395 (R KELTIE) NAVAL SEA SYSTEMS COMMAND 1339 PATTERSON AVE SE STOP 8840 WASHINGTON NAVY YARD DC 20376-8840	1

	Copies
PROGRAM EXECUTIVE OFFICE ATTN PMS403 LITTORAL & MINE WARFARE - UUV 614 SICARD ST SE STOP 7014 WASHINGTON NAVY YARD DC 20376-7014	1
COMMANDER ATTN 4121 (K BEHAN) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
COMMANDER ATTN 4122 (W BARKER) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
COMMANDER ATTN 3496 (T MCELROY) NAVAL UNDERSEA WARFARE CENTER NEWPORT DIVISION 1176 HOWELL ST NEWPORT RI 02841-1708	2
DEFENSE TECHNICAL INFORMATION CENTER 8725 JOHN KINGMAN ROAD SUITE 0944 FORT BELVOIR VA 22060-6218	1
NON DoD	
TITANIUM METALS CORPORATION ATTN JAMES GRAUMAN P O BOX 2128 HENDERSON NV 89009	1
PCC STRUCTURALS INC ATTN RON TRUDO 4600 SE HARNEY DRIVE PORTLAND OR 97206	1
INTERNAL DISTRIBUTION	
CODE 60	1
CODE 61	1
CODE 612	1
CODE 613	1
CODE 613 (AYLOR)	1
CODE 614	2
CODE 614 (CZYRYCA)	5
CODE 614 (FOCHT)	1
CODE 614 (J GAIES)	1
CODE 614 (HAYDEN)	1

Distribution

		Copies			Copies
CODE 614	(IORIO)	1	CODE 615		1
CODE 614	(L'HEUREUX)	1	CODE 615	(WELLS)	1
CODE 614	(MERCIER)	1	CODE 615	(TRAN)	1
CODE 614	(MOUSSOUROS)	1	CODE 65		1
CODE 614	(PURTSCHER)	1	CODE 651		1
CODE 614	(ROE)	1	CODE 652		1
CODE 614	(STAUFFER)	5	CODE 653		1
CODE 614	(STILES)	1	CODE 654		1
CODE 614	(ZHANG)	1	CODE 3442	(TIC)	1

NAVSEA

WARFARE CENTERS

CARDEROCK